Pinch analysis for the planning of power generation sector in the United Arab Emirates: A climate-energy-water nexus study

Pinch Analysis for the Planning of Power Generation Sector in the United Arab Emirates: A Climate-Energy-Water Nexus Study

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Abstract

The United Arab Emirates has recently announced its 2050 Energy Plan, which aims for a 50% clean energy supply. The plan requires diversifying the nation's energy mix and adoption of more renewable energy sources. In addition, climate change and water scarcity issues are key factors to consider towards building an environmentally sustainable future in the country. Therefore, this paper uses Pinch Analysis to examine the 2050 target, focusing in three key aspects (i.e., carbon emissions, energy return on investment, and water footprint) of the country's power sector. Different scenarios for achieving the 2050 target are studied, accounting for demand growth, energy resource availability, and finally technology feasibility and cost projections. This approach provides a holistic assessment of the impact of each of the three aspects on the power generation sector. By constraining United Arab Emirates carbon emissions to 2012 levels, with maximum energy return on investment and minimum water footprint, the electricity sector in 2050 will be dominated by renewable energy, and particularly solar power. Furthermore, the interdependencies of energy and water policy issues are discussed.

Keywords

Electricity; carbon emissions pinch analysis; process integration; energy planning; power sector planning; carbon capture and storage

1. Introduction

Climate change and fossil fuel resource depletion have driven many countries to look for more sustainable energy resources. This trend is true even for countries in the Middle East that are known for their huge reserves of hydrocarbons, such as the United Arab Emirates (UAE), which is currently the world's third largest net oil exporter (EIA, 2017). Since last decade, UAE has enjoyed robust economic development, which coupled with population growth has resulted in a sharp rise in energy demand (Mondal et al., 2014). UAE electricity generation has increased dramatically in recent years, and is generated almost entirely by natural gas-fired power plants (Juaidi et al., 2016). The UAE government has realized that renewable energy should play a more prominent role in the future energy mix to ensure sustainability of the country's development in the long term. This is reflected in the nation's agenda, in which the share of natural gas in the power mix will be reduced from 98% to 76% by 2021 (Ministry of Energy, 2016), and further down to 38% by 2050 (Gulf News, 2017).

Besides ensuring energy security, reduction of CO_2 emissions through diversification of the energy mix is also part of the UAE's priorities as contribution to the global climate change problem, as communicated to the United Nations Framework Convention on Climate Change (UNFCCC) in the country's Intended Nationally Determined Contribution (INDC) report (UNFCC, 2015). According to the latest statistics, the CO_2 emissions of the UAE increased by 63% between 2000 and 2010 (Ministry of Energy, 2015). Although the UAE is categorized by the UNFCCC as a non-Annex I Party that has no legal obligations to reduce emissions, the government has nevertheless committed to reduce CO_2 emissions by 15% by 2021 (Ministry of Energy, 2015). Since electricity generation from fossil fuels is responsible for almost half of the country's total emissions (Mondal et al., 2014), the primary focus for the country's emission reduction is the electricity generation sector.

The UAE is in a unique situation in terms of energy and water resources. It is estimated that the Gulf Corporation Council (GCC) region in which it belongs has two-thirds of global crude oil reserves, but only 1.4% of the world's fresh water supply (Griffiths, 2017). Water planning is thus an important criterion in the country's development roadmap; the UAE ranks in the top 25 among countries for usage of water, primarily due to its petrochemical production and electricity generation (Spang et al., 2014). Thus, water footprint needs to be considered even in energy planning problems due to the inherent interdependencies of these two aspects in the water-energy nexus (Siddiqi and Anadon, 2011). While renewable energy offers the advantage of sustainability, some techno-economic drawbacks hinder its wide integration into the grid energy mix. Some of these issues are low reliability and availability, as well as high capital cost. For the latter issue, the metric known as *energy return on energy investment* (EROI) provides a thermodynamically-based index that can serve as a proxy for economic value (Cleveland et al., 1984).

Clearly, a major shift is currently taking place in the UAE energy sector towards increased use of low-carbon technologies. Energy planning considering carbon emissions, EROI and water footprint are important to ensure the sustainable generation of electricity in the UAE. The country's energy diversification is a high-level policy goal, but detailed analysis of the combination effect from the emissions to the energy expended and water use has not yet been thoroughly studied. As such, this paper utilizes *Carbon Emissions Pinch Analysis* (CEPA) (Tan and Foo, 2007) and its extensions to examine the implications of the proposed energy mix targets on the carbon emission levels, as well as energy expended for capital investments, and water consumption. Two scenarios are analyzed based on official

UAE government projections. This work thus serves as a platform to provide insights into the UAE electricity sector for the provision of sustainable energy. While this paper deals specifically with the UAE, many of the lessons drawn from the analysis can apply to other countries in the GCC, as well as in other regions where long-term availability of water resources may be threatened by climate change.

2. Methodology and data

2.1 CEPA theory and methods

Process Integration may be formally defined as "*a holistic approach to design and operation that emphasizes the unity of the process*" (El-Halwagi, 1997). Process Integration techniques such as *Pinch Analysis* were originally developed in the 1970s to address energy conservation problem in the process industry (Linnhoff et al., 1982). In the 1980s, this framework was extended to address industrial waste minimization problems (El-Halwagi and Manousiouthakis, 1989). Many of the developed techniques are now available in textbooks, such as those for heat integrated processes (Smith, 2016), material resource conservation (Foo, 2012), as well as a handbook (Klemeš, 2013) and encyclopedia chapter (El-Halwagi and Foo, 2014).

CEPA is an extension of the Pinch Analysis technique that focuses on carbon-constrained sectors, where specific carbon footprint limits are imposed on the planning of different energy resources (Tan and Foo, 2007). In particular, CEPA and its variants have been widely studied for electricity generation sector at regional and national levels, including California (Walmsley et al., 2015), China (Jia et al., 2016), Ireland (Crilly and Zhelev, 2008), New Zealand (Atkins et al., 2010) and India (Krishna Priya and Bandyopadhyay, 2013). Furthermore, the basic CEPA framework has been extended to account for other sustainability metrics, such as land footprint (Foo et al., 2008), water footprint (Tan et al., 2009a), *emergy* transformity (Bandyopadhyay et al., 2010), and EROI (Walmsley et al., 2014). Recent works have been reported to account for financial aspects in the CEPA problems, such as the case for India (Chandrayan and Bandyopadhyay, 2014) and Philippines (Tan et al., 2017a). Structural similarities of different footprint-constrained energy planning problems are discussed in a book chapter by Tan and Foo (2013). Recent attempts to extend the CEPA framework to simultaneously account for multiple metrics have been reported by Jia et al. (2016), and more recently in conjunction with the Analytic Hierarchy Process (AHP) by Patole et al. (2017). Other variants of CEPA take into account technological issues, including deployment of carbon capture and storage (CCS) at scale (Tan et al., 2009b). Key developments are surveyed in a recent review paper (Foo and Tan, 2016), while a brief tutorial can be found in a recently published encyclopedia chapter (Tan and Foo, 2017).

The most commonly used graphical tool in CEPA is the *energy planning pinch diagram* (EPPD) (Tan and Foo, 2007), with a generic version shown in Figure 1. As shown, the EPPD consists of the demand and source composite curves. The source composite curve is plotted with cumulative quantity of total carbon dioxide equivalent emissions (CO_2-e) generated from the several fuel sources on the y-axis against the total electricity generated from these sources on the x-axis. Each energy source is plotted as a segment so that its electricity output (in TWh) and carbon emissions (in Mt CO_2-e) lie along the horizontal and vertical axes of the diagram. Consequently, the slope of each segment corresponds to its carbon emission factors (EF), measured in Mt-CO_2-e/TWh. The energy source with the lowest carbon EF is plotted first, followed by the next highest, and so on. The demand composite curve is also plotted in the similar fashion, to represent the regions or sectors that require the electricity.

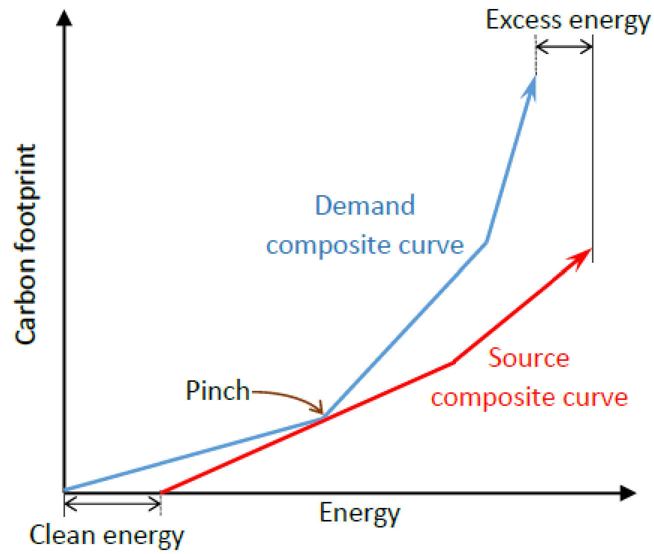

Figure 1. Energy planning pinch diagram (EPPD) (Tan and Foo, 2007).

For a feasible EPPD, the source composite curve has to stay entire below and to the right of the demand composite curve. For cases where this condition is not met, the source composite curve has to be shifted horizontally to the right, so that it only touches the demand curve at the Pinch Point. The resulting gap on the left is the minimum amount of clean (i.e., zero-carbon) energy resources that need to be added in order to meet the system's specified emissions limits. The overhang of the source composite curve on the right corresponds to the amount of excess resources. The equivalence of CEPA to mathematical programming is well known (Tan and Foo, 2007), and recently the P-graph equivalent has also been proposed (Tan et al., 2017b). While mathematical programming is a well-established tool for planning, there remains a need for simplified representation of complex problems to facilitate decision-making and communication (Geoffrion, 1976). As a result, even with the growth of computing power since the 1970s, Pinch Analysis remains a valuable complementary approach to mathematical programming in conventional Process Integration applications (Klemeš and Kravanja, 2013). For sustainable energy planning, the visually-oriented display of data in CEPA is especially useful in providing direct insights for decision-makers (Foo and Tan, 2016), and can be used in conjunction with more detailed mathematical programming models.

2.2 Energy returned on energy investment (EROI) analysis

The concept EROI was first proposed by Hall (1972) as a means of calculating the ratio between the energy delivered by a particular fuel to society and the energy invested in the capture and delivery of this energy (Hall et al., 2014). A minimum EROI of approximately 3 is needed for a system to be economically viable, based on the argument that energy flows serve as a proxy for economic flow of goods (Hall et al., 2009).

EROI involving electricity generation is defined by Equation 1.

$$EROI_{gen} = \frac{\dot{E}_{gen}}{\dot{E}_{ED} + \dot{E}_{PP}} \quad \text{Equation 1}$$

where $\dot{E}_{gen}$ is the amount of useful or gross energy produced, the total energy expended ($\dot{E}_{ED}$) is the sum of all the inputs needed in the extraction, processing and distribution operations of the fuel, and $\dot{E}_{PP}$ is the additional energy required for electricity generation which includes internal electricity use, direct fuel inputs, indirect energy inputs (e.g., labour, material and resource), some of which is the embedded energy of construction and decommissioning that must be spread over the expected system lifetime (Walmsley et al., 2014).

The life cycle of a technology and availability of energy source affects its EROI ratio. As technology matures, EROI generally improves. On the other hand, renewable energy sources are strongly dependent on climate and geographic location. Climatic conditions can change dramatically in both short term (on a time scale of minutes, hours and days) and long term (over a time scale of years or decades) and this can have a significant effect on EROI due to the need for back-up generation capacity or energy storage systems. For renewable energy, the bulk of the costs arise from required access to large amounts of land to harvest it, as well as huge expenditure in terms of energy and cost to build infrastructure, storage facilities and equipment to harness the dispersed and low intensity of the renewable energy resources (Walmsley et al., 2015). Therefore, their EROI values are typically lower than the conventional fuels, as shown in Table 1.

Since climate issues has become an important design criterion, additional energy expended for CCS ($\dot{E}_{CCS}$) can be included to calculate an equivalent carbon neutral EROI for electricity generation, as developed by Walmsley and co-workers (Walmsley et al., 2014), see Equation 2. The energy expended for CCS includes energy used in the CCS process operation, construction and decommissioning of the CCS plant and extraction of additional fuel for use in CCS. Estimates based on a case study of power station with CCS indicated that among the various components of $\dot{E}_{CCS}$, about 95% of the energy consumed is associated with the CCS operation lifecycle. Corresponding to this, an approximation for $\dot{E}_{CCS}/\dot{E}_{gen}$ was established from Walmsley et al. work (Walmsley et al., 2014) and is applied here. The $\dot{E}_{CCS}/\dot{E}_{gen}$ is a function of electricity generation thermal efficiency, carbon emission factor of the fuel alone, acceptable level of emissions of the plant and the specific total energy required (thermal and electrical) for the capture and sequestration of CO_2-e. Therefore, $EROI_{gen,CCS}$ is related to $EROI_{gen}$ as shown in Equation 3.

$$EROI_{gen,CCS} = \frac{\dot{E}_{gen}}{\dot{E}_{ED} + \dot{E}_{PP} + \dot{E}_{CCS}} \quad \text{Equation 2}$$

$$EROI_{gen,CCS} = \frac{1}{EROI_{gen}} + \frac{\dot{E}_{CCS}}{\dot{E}_{gen}} \quad \text{Equation 3}$$

The concept of EROI was first incorporated into EPPD by Walmsley et al. (2014). The inverse of the EROI is used as the quality index.

2.3 Water consumption for electricity generation

There are strong water-energy interactions due to the heavy use of water in energy systems, (Varbanov, 2014). Water footprint is thus an important metric for assessing energy systems (Mekonnen et al., 2015). In this work, water used to produce and transform the fuels used by electric sector is excluded, along with all other indirect water demands of the power plant (Spang et al., 2014).

Water intensity data from literature are used in this study (Macknick et al., 2011). The numerical values are listed in the last column of Table 1. These intensity values vary substantially with different combinations of electricity generation technologies and cooling systems. It is noteworthy that renewable power sources use relatively less water as compared to fossil fuel-fired and nuclear power plants Advanced fossil-fuel technologies such as natural gas combined cycle have lower water intensity due to higher efficiency, while CCS retrofitting incurs water footprint penalties associated with efficiency reduction (Fricko et al., 2016).

To reflect water footprint issues, water intensity (in unit of km^3/TWh) can be used as a quality index in EPPD (Tan et al., 2009a).

2.4 Data sources

The carbon emission factor, $EROI_{gen}$ and water intensity used in this analysis are consolidated from the literature and selected from the most recent statistical reports. The key data are given in Table 1.

Table 1. Summary of emission factors, EROI values and water intensity used in this study.

Energy sources	Carbon Emission factor ($MtCO_2$-e/TWh)	$EROI_{gen}$ / $EROI_{gen,ccs}$	Water Intensity (km^3/TWh)
Coal	0.99[a]	25[a,c]	-
Coal-CCS	0.22[b]	2.7	2[d]
Gas	0.61[a]	35[a,c]	0.4[d]
Gas-CCS	0.2[b]	0.7	1.4[d]
Nuclear	0	8[a]	2.5[d]
Renewables	0	7[a,c]	0.1[d]

Data sources: **a**: (Jia et al., 2016); **b**: (Allen, 2011); **c**: (Walmsley et al., 2014); **d**: (Davies et al., 2013)

3. UAE electricity sector

3.1 Electricity generation planning for UAE through to 2050

The total electricity generation in the UAE was recorded at 102 TWh in 2012 (IRENA, 2015). The figure is expected to increase continually with an average rate of 5.5% per year (Ministry of Energy, 2015). Therefore, the extrapolated UAE electricity demand of 2021 (164 TWh) and 2050 (777 TWh) are shown in Table 2. The seven-year roadmap of UAE National Agenda Vision 2021 has committed to produce 24% of clean energy to generate electricity, mainly from nuclear and renewables (UNFCC, 2015). As there is no official data available on the breakdown of the clean energy announced and taking into account that the 5.6 GW nuclear power plant now being built is expected to provide around 20% of the energy needs by 2020, the energy mix in 2021 is likely to consist of mainly nuclear and natural gas generation (IRENA, 2015). Other clean energy sources in place include waste-to-energy and wind power but in much smaller scale, hence will be grouped together with solar as renewables energy source that contributes around 1% of the total generation mix in 2021. The nation's government has projected the 2050 energy plan aiming to diversify the UAE energy mix to 50% clean energy (6% nuclear + 44% renewable), 38% gas and

12% coal (Gulf News, 2017). It is noteworthy that the clean coal combustion herein are designed to be carbon capture, storage and utilization (CCSU) ready (Ministry of Energy, 2015).

Table 2. Power generation statistics for UAE in 2012, 2021 and 2050.

	Power Output (TWh)				
Energy sources	Nuclear	Renewables	Coal-CCS	Gas	Total
Year					
2012	0	0	0	102	102
2021	37	2	0	125	164
2050	47	342	93	295	777

Use of renewables in UAE began in 2008 by having several small scale projects of solar and wind installed and connected online, such as 10 MW Masdar City Photovoltaic (PV), 29 MW Sir Bani Yas Wind Farm and 100 MW Shams 1 concentrated solar power (CSP) plant. Larger scale developments, such as 1000 MW Mohammed bin Rashid Al Maktoum Solar Park, Shams Dubai Initiative (also known as Distributed Renewable Resources Generation, DRRG programme) have also been gradually deployed (Griffiths, 2017). Solar PV is currently viewed as the most attractive renewable technology for the UAE (Juaidi et al., 2016). Its local cost has substantially fallen around 75% since 2008 and is potentially competitive with fossil fuels (IRENA, 2015).

The cumulative electricity output and carbon emissions of the years 2012, 2021 and 2050 are illustrated in Figure 2. The total emissions for UAE in 2012 were 62 Mt CO_2-e; 76 Mt CO_2-e by 2021 and 200 Mt CO_2-e in 2050. The use of cleaner energy resources in 2021 is expected to lower grid emission factor (GEF) of 0.46 Mt CO_2-e/TWh compared with 0.61 Mt CO_2-e/TWh in 2012 of conventional gas power generation. In 2050, the GEF is further decreased to 0.26 Mt CO_2-e/TWh. Note that the emissions factor for both nuclear and renewable energy exclude those arising from capital investments (Walmsley et al., 2014). Others have reported a variety of life cycle emission factors and they vary considerably depending on the location and technology of the generation, conversion efficiency and capacity factor and plant life used (Tan et al., 2009b). Despite the variation, the emission factors estimate for the renewables and nuclear are typically at least one to two orders of magnitude lower than the fossil-fuel based thermal generation and can be approximated as zero. The emission factor of coal with CCS is extracted from UK data (Allen, 2011). Recently, two clean coal projects in the UAE have been launched in GCC regions to diversify power supply (Ministry of Energy, 2016).

Per capita electricity consumption in the UAE is among the highest in the world, at approximately 12500 kWh per year (Ministry of Energy, 2015). To support the country's green economic development, strategies for reducing energy consumption play an important role (Ministry of Energy, 2016). Ambitious targets have been set by the government to reduce energy demand by 30% in 2021 and 40% in 2050 (Gulf News, 2017). By maintaining the electricity generation mix distribution, cumulative electricity output with the targeted reduction in 2021 (115 TWh) and 2050 (466 TWh) are shown in Figure 2. The cut in 2050 alone results in energy saving of 310 TWh from the business as usual scenario, equivalent to three times the energy used as of year 2012 consumption pattern. It is worth noting that solely by energy savings in 2050 still gives a net output of carbon emission of 58 (=120-62) Mt CO_2-e compared with year 2012 emission as baseline. Unlike the energy reduction target of 2021 which shows a positive contribution to the environmental impact where 9 Mt CO_2-e (= 62 – 53 Mt) of carbon emission is reduced.

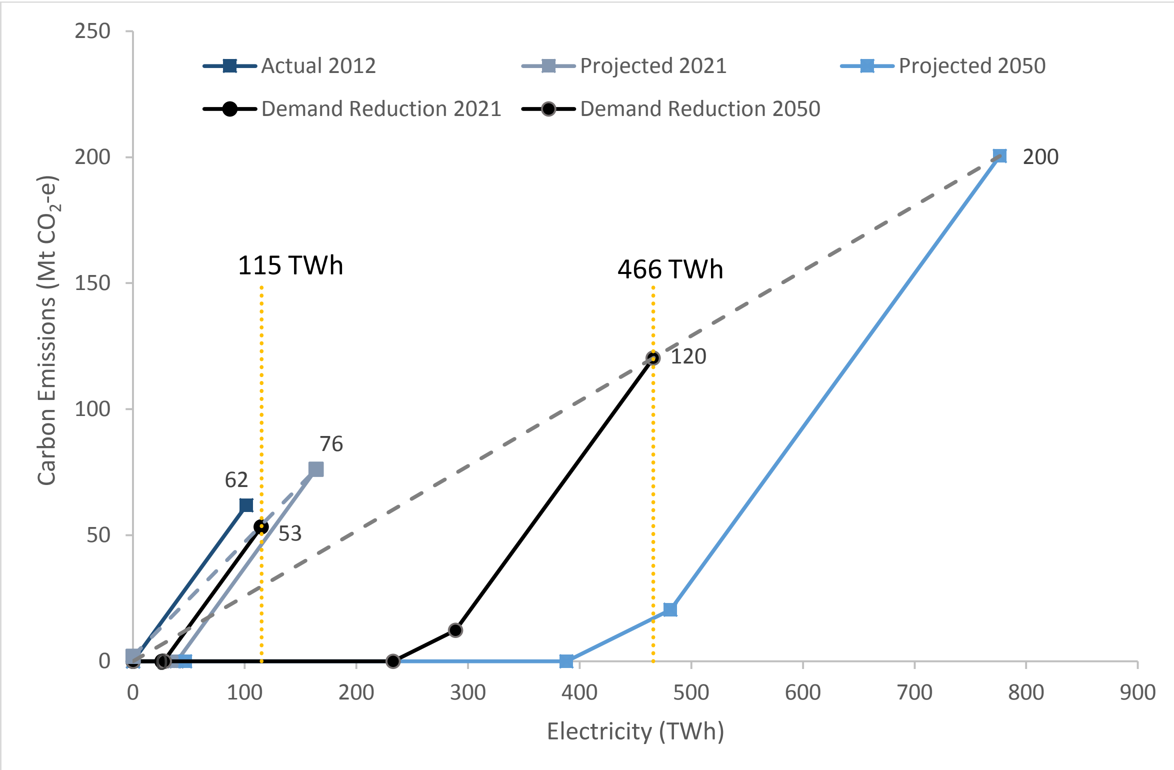

Figure 2. Estimated carbon emissions from UAE electricity generation of 2012, 2021 and 2050.

3.2 Case Study: Carbon Emission Pinch Analysis (CEPA) of the UAE electricity sector in 2050

A baseline benchmark for the country electricity sector carbon emissions has yet to be set (Ministry of Energy, 2016). Therefore, in this analysis, a reduction in emission levels to 2012 level while simultaneously meeting increased demand by 2050 is assumed. The official projected generation mix of 2050 with 40% energy demand reduction is used as the supply basis. Since adoption of renewable-energy comes with the risk of reduced reliability and availability, base load power generation will still rely on fossil fuels and nuclear energy. In addition, it is also considered infeasible to discontinue operations of existing fossil fuel-fired plants if they have not yet fully expended their projected economic lives, unless external costs of greenhouse gas emissions are taken into account. As a result, two scenarios are investigated in this study: (1) increase of clean energy sources and (2) CCS retrofits in existing gas power plant.

3.2.1 Scenario 1 – Increase of clean energy sources

In the first scenario, additional amount of 100 TWh clean energy is needed to satisfy the total electricity demand of 466 TWh while reducing emissions to 2012 level, as illustrated by the EPPD in Figure 3. As shown, the source composite curve is shifted to the right to meet the carbon emission target. This indicates that the amount of natural gas source would also be reduced by 100 TWh with the extra clean energy source added into the generation mix, resulted an increase to 71% of clean energy (6% nuclear +

65% renewable), coal remains 12% and gas reduce to only 17% in the generation mix, as oppose to the projected of 50% clean energy (6% nuclear + 44% renewable) and 38% of gas.

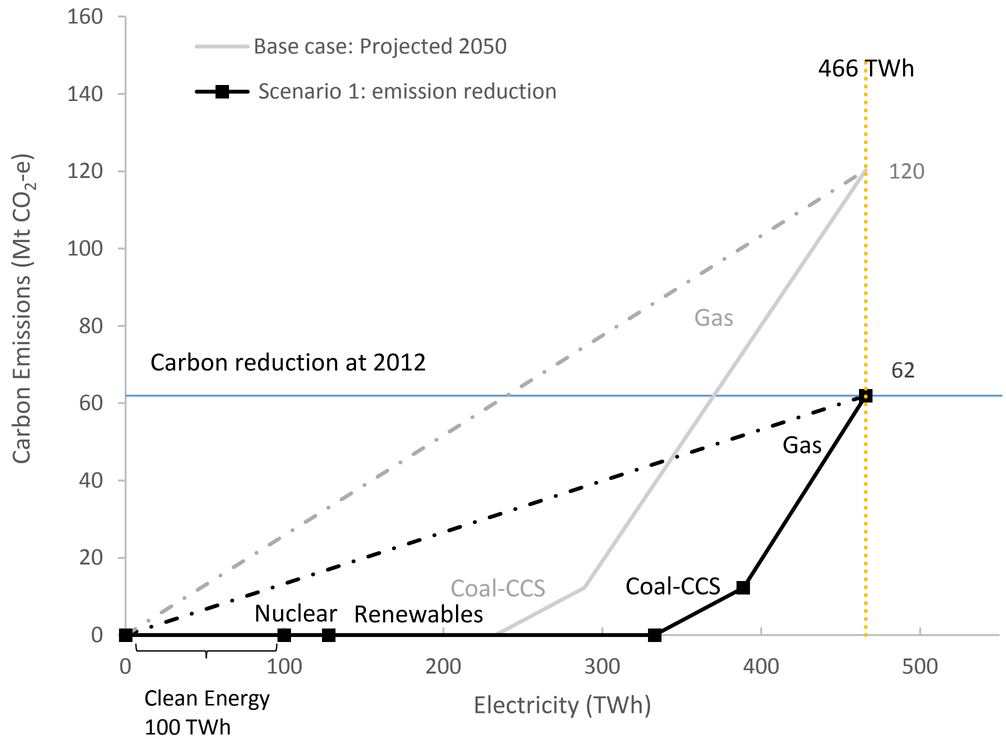

Figure 3. Scenario 1-Targeting more clean energy to meet 2012 carbon emission level.

Solar PV's scalability, operating simplicity and low unit cost make it ideal for arid tropical conditions in the UAE. On the other hand, the wind resources are restricted to specific geographic locations only (Sgouridis et al., 2016). Thus, the additional clean energy of 100 TWh depicted in Figure 3 will contribute mostly from solar.

3.2.2 Scenario 2 – CCS retrofits in existing gas power plant

CCS is considered to be the only available option at the moment to allow clean fossil fuel technologies to continue operating widely without contributing excessively to global warming. Most of the UAE gas power plants are currently employing combined cycle gas turbine technology (Lin et al., 2011). In order to reduce carbon emission level, the second scenario proposed herein is retrofitting these plants for CCS to reduce emissions intensity by a factor of three (Allen, 2011). Coal-CCS produces a comparable carbon emission as a Gas-CCS system. Figure 4 shows the EPPD with 80% of the energy from natural gas power plant in 2050 (i.e. 142 TWh of the total 177 TWh) needs to be CCS retrofitted in order to meet the carbon emission at 2012 levels.

Both scenarios 1 and 2 gave around 50% reduction in emissions and half of GEF (0.13 Mt CO_2-e/TWh) than the official projected generation mix. It is important to note that it does not limit to only these two scenarios presented here that can fulfill the carbon emission reduction goal, but these are currently considered the more viable options with existing resources and technology.

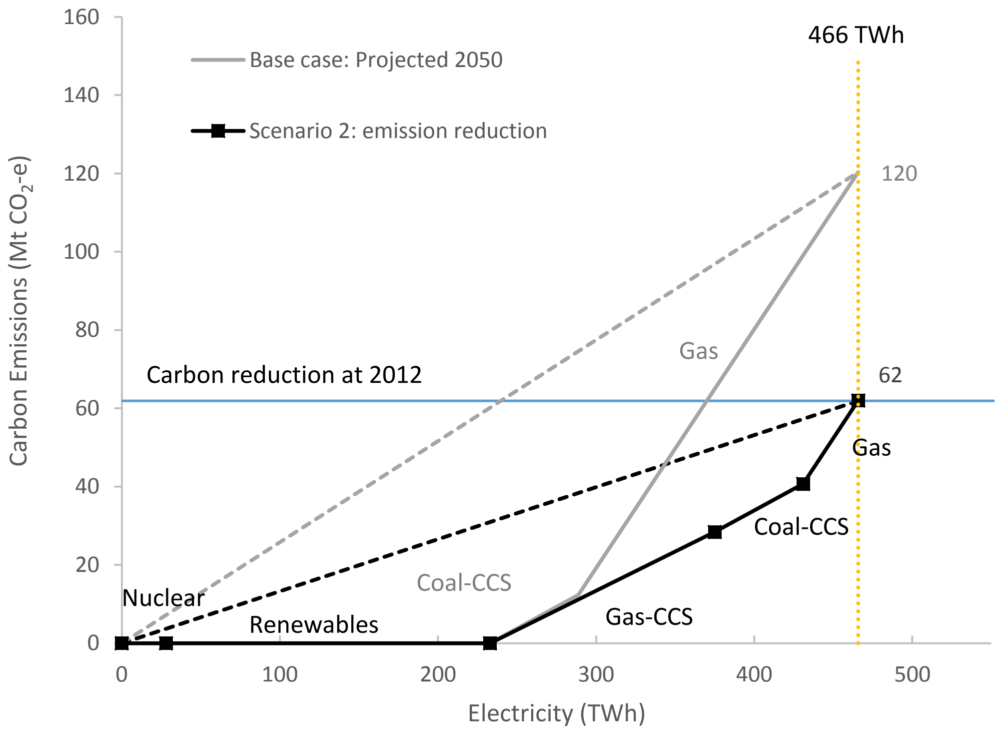

Figure 4. Scenario 2- Gas power plant retrofitted with CCS to meet 2012 carbon emission level.

3.3 EROI analysis of the UAE electricity sector in 2050

The energy expended values are estimated using EROI values presented in Table 1. Conventional fossil fuel such as coal, oil and natural gas have relatively high EROI values compare with other renewable or clean technologies at this point in time. Its high EROI value reflects the low amounts of expended energy due to the technology advancement and maturity. However, recent studies indicated that the fossil fuel EROI values will continue to decline due to the depletion of these limited resources (Hall et al., 2014). Renewable energy sources are generally characterized by lower EROI values, and are considerably less attractive to be exploited than the major fossil fuels source. To take into account of the carbon emissions produced by the resources, additional expended energy term for CCS is included in the calculation of EROI as proposed by (Walmsley et al., 2014).

The official projected electricity generation mix of 2050 with average EROI value of 8 is illustrated in Figure 5. By comparison, the average EROI across the UAE electricity sector in 2012 was 35 and 20 in 2021 (not shown). The decrease of EROI is mainly due to the addition of clean energy sources. It is noteworthy that there is a vast difference in terms of the priority order of each resources in environmental carbon impact and the energy return point of view. From the cost of production as seen in Figure 5, gas is favourable, but it comes with higher CO_2 emissions as noticed in Figure 3. For many resources there is a natural conflict between achieving a high EROI while at the same time minimizing emissions (Walmsley et al., 2014).

With the targeted carbon emission at 2012 levels by 2050, the energy investment cost is further compared for the two scenarios studied above. The first scenario with more clean energy in the generation mix resulted in a slight increase of 20% in energy cost due to higher portion of low EROI renewables compare with the projected 2050 without any carbon reduction measures. Widely deploying CCS to lower emissions causes a significant EROI penalty. The average EROI values are obtained for both Scenarios 1 (6.7) and 2 (1.9). By including the energy-intensive CCS, the solution is dominated by the clean energy resources (Scenario 1). Evidently, a better energy investment strategy is expanding the renewable generation, rather than gas-CCS power plants (Scenario 2).

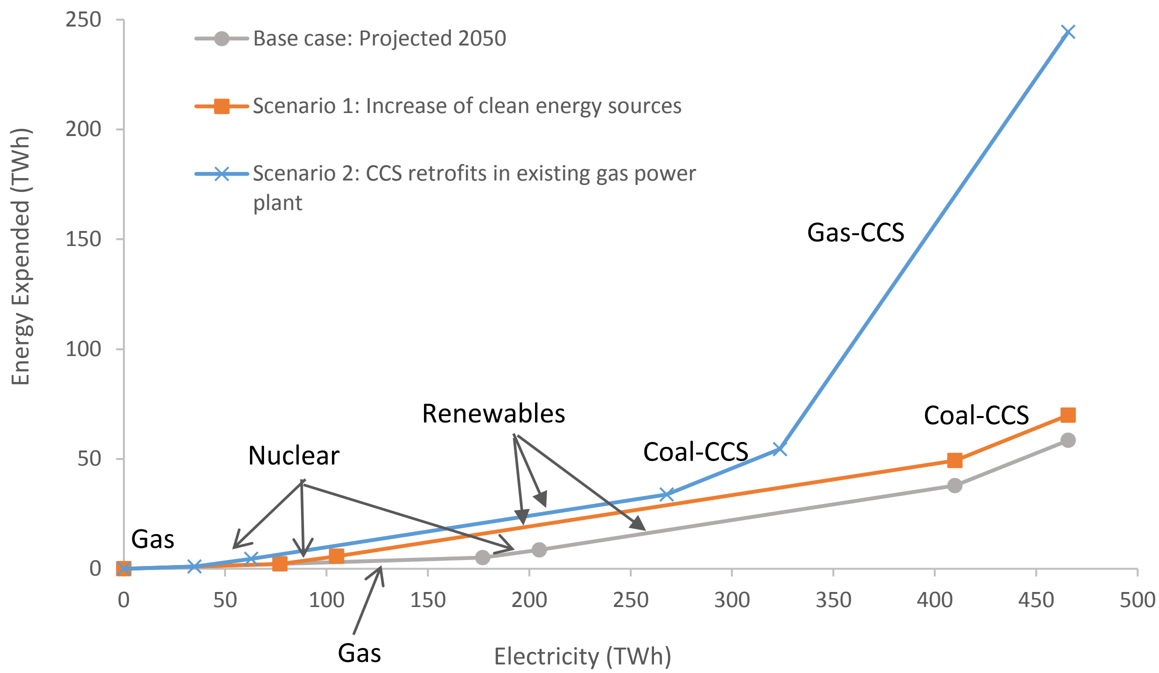

Figure 5. Energy expended for UAE electricity generation in 2050 featuring base case, Scenario 1 and Scenario 2 of carbon emissions reduction.

3.4 Water footprint in the UAE power generation sector through to 2050

To meet the rising demand for electricity, it is important to predict the water needs of the power generating sector in view of the water security and scarcity crisis of the UAE arid climate. There has been a dramatic change in the UAE water sources in the recent decade, where almost all water supplies in UAE based entirely upon desalination source as opposed to increasingly depleted groundwater sources (Ministry of Energy, 2016).

A distinctive feature in most of the power plants in UAE is the cogeneration systems that produce both water and electricity. These integrated systems use both heat and electricity for desalination (Lin et al., 2011). There has been a clear shift towards decoupling the water and electricity production due to two main factors (Paul et al., 2016). Firstly, there is a drop of the overall plant efficiency as a result of the inconsistent demand in water and electricity, since efficient desalination requires the availability of waste heat. Secondly, the volatility and increase of natural gas price in recent years have been impacting the power sector in the UAE (Ministry of Energy, 2016). To make a quantitative comparison on the water impact of the UAE 2050 energy mix scenarios in the power sector, decoupling effect is considered and all power plants are assumed to be power-only-plant in this work.

For the renewables energy source, which is dominated by a mix of solar PV and CSP, the water intensity is marginally low. Although recent study have indicated that CSP (unlike PV) uses as much water as nuclear (Fricko et al., 2016) for wet cooling, the Shams 1 CSP in UAE have successfully operated with dry-cooling system, which significantly reduces the water consumption (IRENA, 2015). It is anticipated that the continued expansion of CSP power plant in the future will be using identical fashion.

With the projected base case power generation resource mix of 2050, the total water consumption is 344 km^3 per annum, as illustrated in Figure 6. The calculated water consumption for UAE power sector in 2012 is about 81 km^3 (not shown). With the proposed Scenario 1 of maximum renewable sources penetration into the power sector generation to achieve the carbon emission at 2012 level, around 70 km^3 of water can be saved. Scenario 2 that features CCS retrofitting for natural gas power plant yielded a higher water consumption rate of 429 km^3 due to higher water demand in the CCS operation. The UAE 2050 energy resource portfolio has shown significant diversion in producing fresh water from the traditional thermal desalination process. Therefore, alternative desalination routes are to be exploited in near future to meet the increasing water demand.

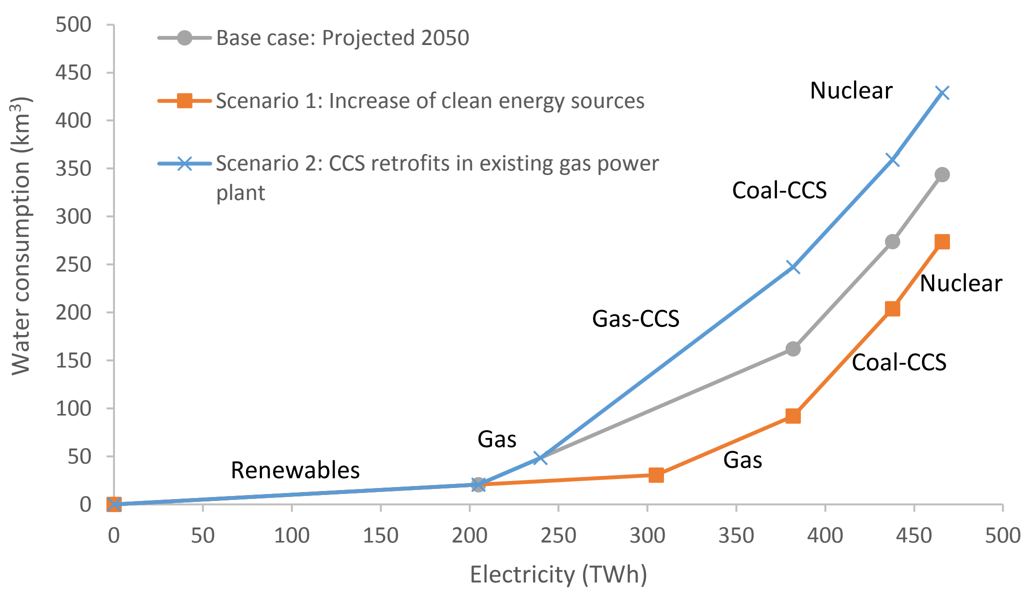

Figure 6. Water consumption for UAE electricity generation in 2050 featuring the base case, Scenario 1 and Scenario 2 of carbon emissions reduction.

3.5 Analysis and discussion on the climate-energy-water nexus

This study focuses on targeting the carbon emission of UAE power sector in 2050 via pinch analysis methodology and further analyzing the impact on EROI and water consumption. With the climate-energy-water nexus approach applied, an increase in renewable energy from the base case of 44% to

Scenario 1 of 65% have clearly demonstrated the advantages in terms of climate and water preservation, with a small penalty incurred in the investment cost (Figure 7). Scenario 2 with CCS employed in both coal and partial natural gas power plants have resulted in higher energy and water demand. Energy expended has a more significant impact than water consumption in solving the climate crisis in power sector, which is in good agreement with other studies that examined the energy-water nexus, in particular (Siddiqi and Anadon, 2011).

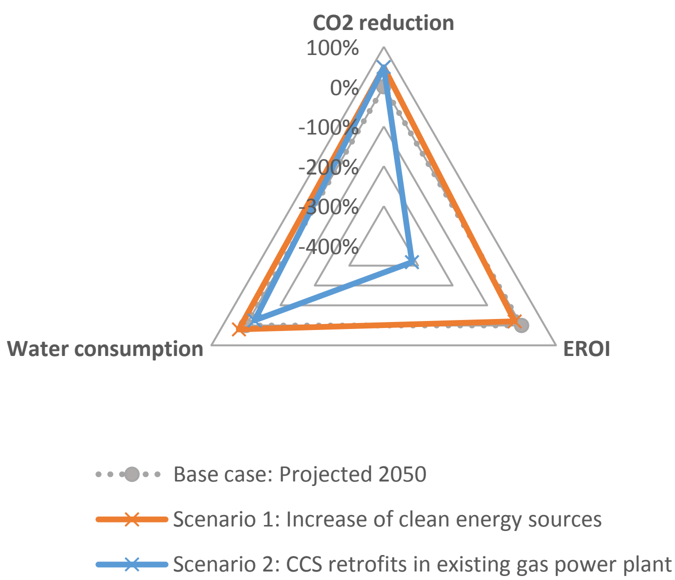

Figure 7: Climate-energy-water nexus study of the two scenarios compared with official projected base case (+ indicates a positive impact, - indicates a negative impact).

Using non-combustion sources with inherently low carbon footprints (e.g., nuclear and renewables) are seen as the crucial part of the global solutions in decarbonizing electricity supply. Under the clean energy category, renewables primarily solar is far more favorable than nuclear when it comes to the social aspect of public concerns (Pietzcker et al., 2014) as well as the water intensity (Fricko et al., 2016). Besides, since UAE electricity consumption is heavily weather dependent, peak electricity demand occurs on summer afternoons due to electricity consumption from air conditioning. This matches with the maximum output from solar power systems thereby they can lead to substantial "peak shaving effects" and reducing the need for building expensive underutilized peak load plants (Pietzcker et al., 2014). Solar power is also reported to be the most cost-effective solution for the global electricity to achieve the 2°C climate target through to 2100 (Pietzcker et al., 2014). Between PV and CSP, in UAE context, EROI and water demand are comparable. However, an important characteristic differentiating PV and CSP is the potential of CSP to use thermal storage and co-firing of gas and hydrogen. At the same time, CSP can be combined with thermally driven desalination plant, similar to the normal gas plant in UAE.

As natural gas supply will be limited in years ahead and may be less accessible to some regions (emirates) in the UAE, an urgent call for alternative energy resources would be expected. Incremental fossil fuel prices would make the scaling up of renewables more financially attractive, especially in hydrocarbon-exporting countries, like UAE where fossil fuel is a key pillar of the economy providing vital revenue via oil and gas exports. As with neighboring GCC countries, part of UAE fossil fuels are consumed locally, which reduces the export potential. Expansion of renewable technologies will be able to free up more fossil source and increase the country export revenues (IRENA, 2016). Increasing renewables in the country have added benefits of enhancing social sustainability through improved employment opportunities at a variety of technical levels as well as healthier living environment which are not captured under this nexus study, but can be part of future work. Although two leading emirates, Dubai and Abu Dhabi have both targeted to increase their renewable supply by 5% by 2020, and 7% by 2030 (Ministry of Energy, 2015), more efforts need to be carried out in federal level to meet at least the 44% renewables of the 2050 projected base case and beyond it to 65% of Scenario 1 recommended in this study.

CCS technology is seen to be part of the promising solution during the interim period of transition from fossil based to low carbon energy system in UAE, despite its disadvantages (Markovska et al., 2016). Nevertheless, UAE has established a track record of having the first Middle East's commercial scale *carbon capture use and storage* (CCUS) facility sequestering up to 800,000 tons of CO_2 per year from the carbon-intensive steel industry. In addition, this captured CO_2 will be used for *enhanced oil recovery* to boost oil production (Ministry of Energy, 2015). With a positive economic (in terms of saving natural gas) and environmental return, the electricity sector can promote CCUS in the UAE and provide key lessons for the rest of the world. Although this comes with a price of lower energy return against renewables and also higher water consumption in the power sector, the actual impact is yet to determine in the bigger context of overall UAE domestic energy market. Also, once the CCS technology becomes more developed, its EROI will be increased appreciably.

To support the move towards alternative energy sources, such as nuclear and renewables, the typical cogeneration of water and electricity system in UAE would be affected. Therefore, the water gap would have to be covered by standalone water production plants such as reverse osmosis (RO) which requires only electricity to operate (Siddiqi and Anadon, 2011) or through hybrid systems (combination of RO with thermal technologies) that offer greater system flexibility and capacity (Paul et al., 2016).

From the energy and water resource standpoint, it is important to carefully consider future possibilities of supply and demand. As aforementioned, peak demand in electricity is highly associated with temperature and seasonal change. Instead of relying on electricity for cooling comfort, district cooling technology can be explored from recovery of 'waste cold' from liquefied natural gas (LNG) (Werner, 2017). Since the UAE uses up to 22% of its total electricity for desalination, there is considerable potential for improvement in this aspect (Siddiqi and Anadon, 2011). The GCC region water security issue is worsen when it comes to the distribution and delivery of desalinated water, where water lost is recorded between the range of 10 and 40% (Abdmouleh et al., 2015). The less explored option is recycled urban wastewater, whose treatment cost is a fraction that of desalination cost (Siddiqi and Anadon, 2011). Nonetheless, a more comprehensive review has to take place to study its full potential and viability.

Finally, the "low hanging fruit" in combating the climate challenge relies on demand side management. A direct and significant positive impact can be achieved by energy efficiency measure in reducing the carbon emission as well as in conserving energy and water supply. Several studies have concluded that demand reduction plays a critical role in future global greenhouse gas emissions from power sector

(Fricko et al., 2016). With UAE ranked as one of the top nation of highest electricity consumption per capita (Ministry of Energy, 2015), unwavering measures have to be adopted to increase public awareness, influence consumer behavior and enforce efficient use of energy and water.

4. Conclusions

In this work, CEPA and its extensions have been applied to a country-level analysis of the UAE's goal of reducing carbon emissions from its electricity generation sector. Energy diversification is one of the main strategies in the national agenda, but the shift towards low-carbon energy sources is subject to EROI and water footprint considerations. To meet the carbon emissions goal, two scenarios have been compared in this study with the official projected base case. Scenario 1 depicts a 65% renewable penetration, while Scenario 2 involves 80% of natural gas-fired plants retrofitted with CCS. By cutting half of the carbon emissions, Scenario 1 improves water footprint by 20% with a slight penalty in energy invested for capital. On the other hand, Scenario 2 resulted in substantially higher energy cost (of 3 to 4 times) and water footprint compared with both the base case and Scenario 1, due to energy- and water-intensive CCS technology. Continued focus on improving renewable energy technologies is still required to make the diversification strategy more viable in the UAE context. The quantitative assessment provides general policy directions to allow for sustainable electricity generation in the UAE in the long term. Future work can focus on the application of CEPA and related tools for other countries that are in the process of implementing energy transitions arising from international commitments. The interplay between energy and water is particularly important, both for arid countries, and for nations whose long-term water resources may be threatened by climate change. Detailed energy planning in the industry and transportation sectors is also needed to complement the insights drawn from this work.

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Captions for tables

Table 1. Summary of emission factors, EROI values and water intensity used in this study.

Table 2. Power generation statistics for UAE in 2012, 2021 and 2050.

Captions for Figures

Figure 1. Energy planning pinch diagram

Figure 2. Estimated carbon emissions from UAE electricity generation of 2012, 2021 and 2050.

Figure 3. Scenario 1-Targeting more clean energy to meet 2012 carbon emission level.

Figure 4. Scenario 2- Gas power plant retrofitted with CCS to meet 2012 carbon emission level.

Figure 5. Energy expended for UAE electricity generation in 2050 featuring base case, Scenario 1 and Scenario 2 of carbon emissions reduction.

Figure 6. Water consumption for UAE electricity generation in 2050 featuring the base case, Scenario 1 and Scenario 2 of carbon emissions reduction.

Figure 7: Climate-energy-water nexus study of the two scenarios compared with official projected base case (+ indicates a positive impact, - indicates a negative impact).

Table 1

Energy sources	Carbon Emission factor ($MtCO_2$-e/TWh)	$EROI_{gen}$ /$EROI_{gen,ccs}$	Water Intensity (km^3/TWh)
Coal	0.99[a]	25[a,c]	-
Coal-CCS	0.22[b]	2.7	2[d]
Gas	0.61[a]	35[a,c]	0.4 [d]
Gas-CCS	0.2[b]	0.7	1.4 [d]
Nuclear	0	8[a]	2.5 [d]
Renewables	0	7[a,c]	0.1 [d]

Data sources: **a**: (Jia et al., 2016); **b**: (Allen, 2011); **c**: (Walmsley et al., 2014); **d**: (Davies et al., 2013)

Table 2

	Power Output (TWh)				
Energy sources	Nuclear	Renewables	Coal-CCS	Gas	Total
Year					
2012	0	0	0	102	102
2021	37	2	0	125	164
2050	47	342	93	295	777

figure 1

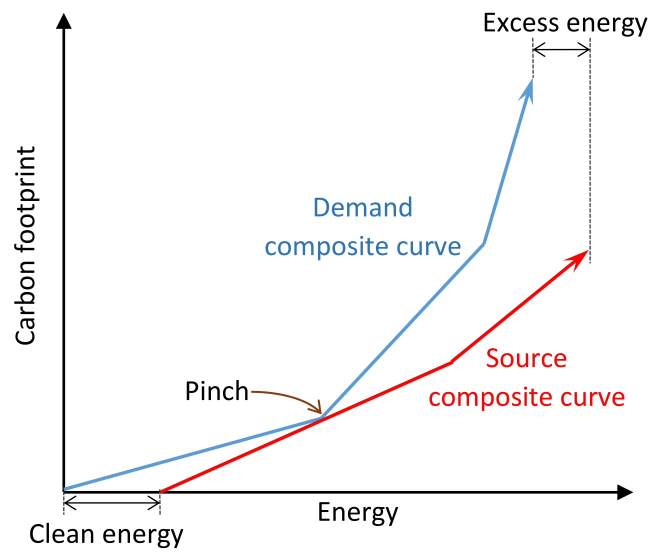

Excess energy
Carbon footprint
Demand
composite curve
Source
composite curve
Pinch
Energy
Clean energy

Figure 2

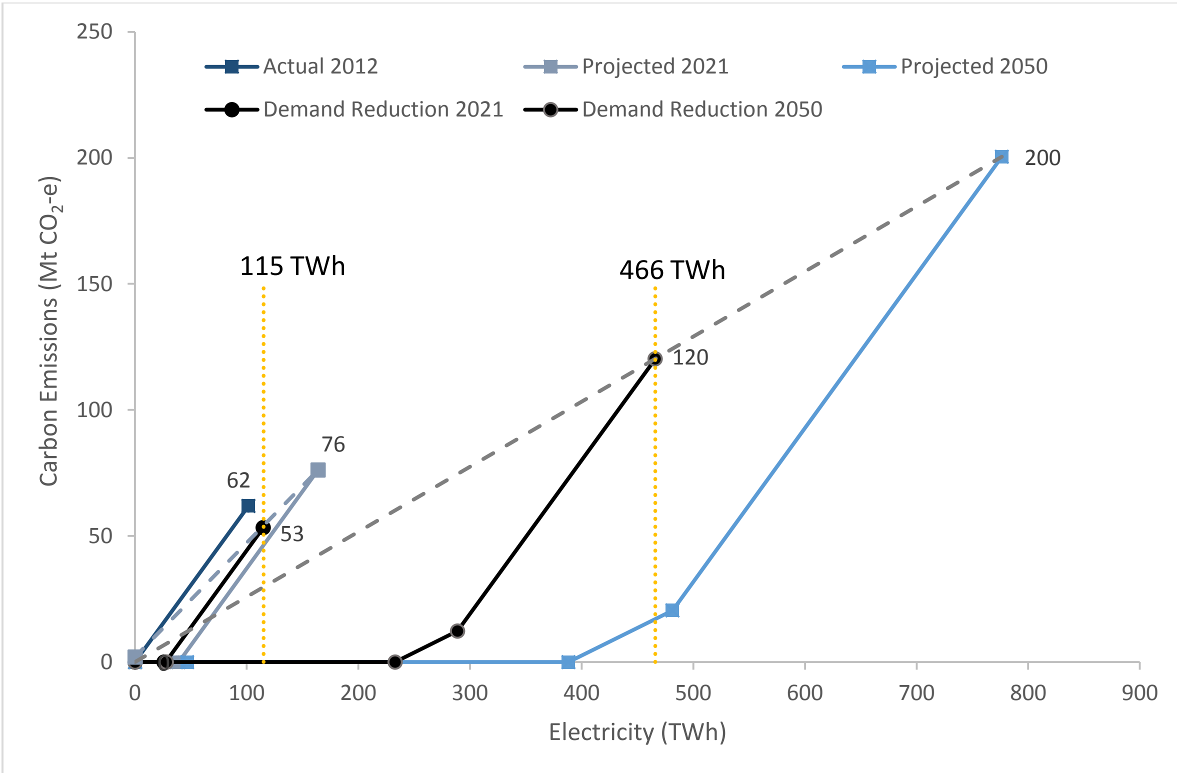

Actual 2012
Projected 2021
Projected 2050
Demand Reduction 2021
Demand Reduction 2050
115 TWh
466 TWh
62
76
53
120
200
Carbon Emissions (Mt CO_2-e)
Electricity (TWh)
0
50
100
150
200
250
0
100
200
300
400
500
600
700
800
900

Figure 3

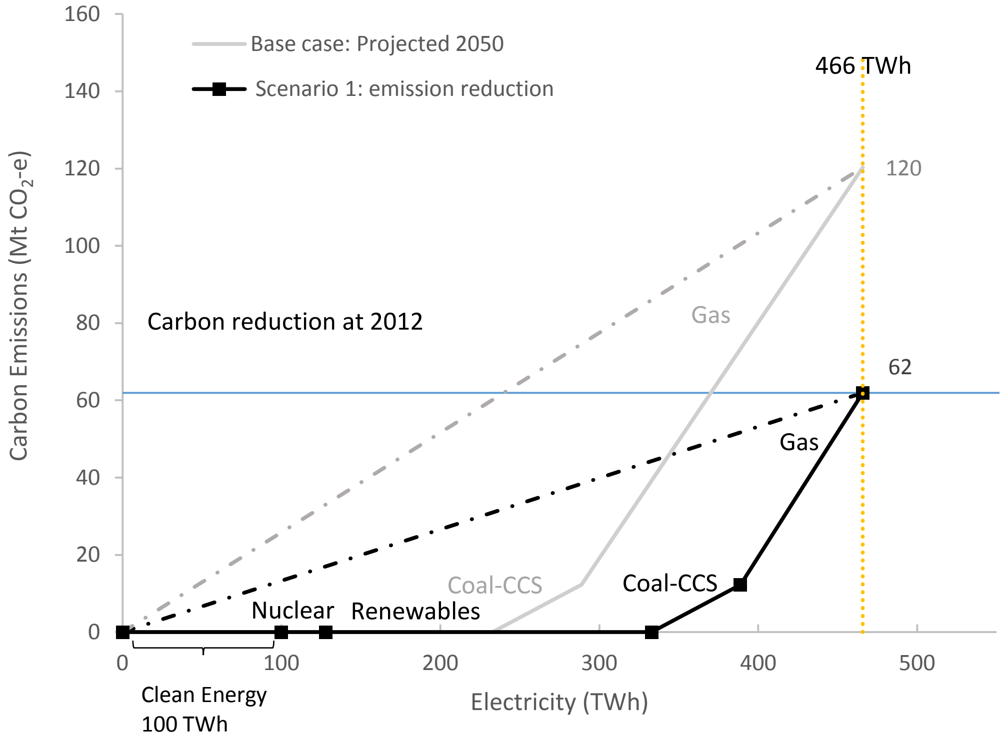
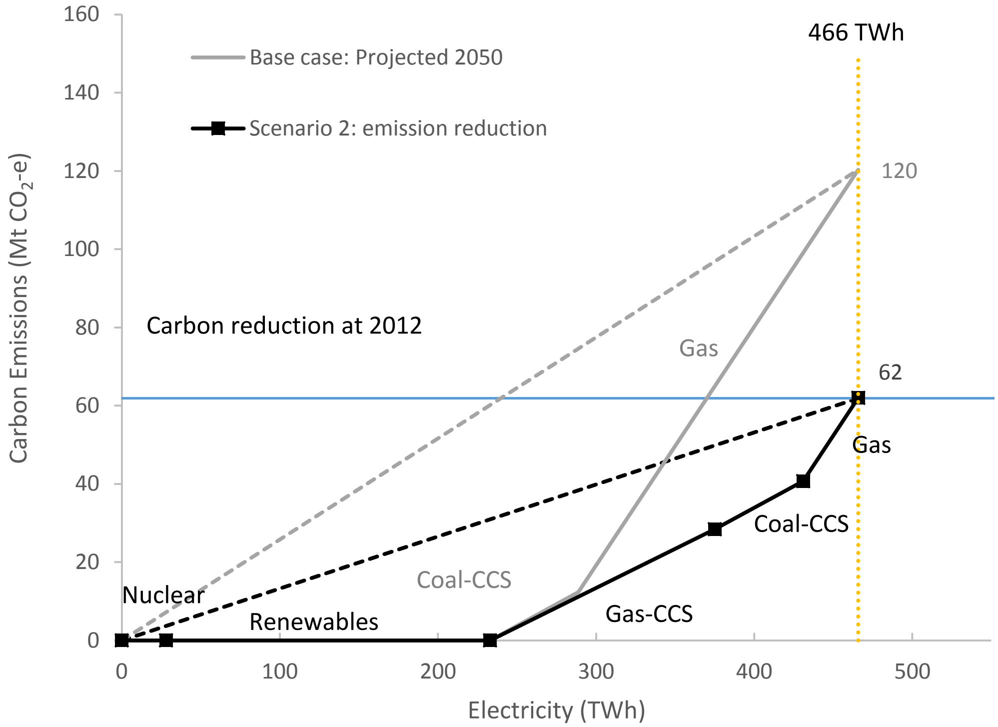

160
140
120
100
80
60
40
20
0
Carbon Emissions (Mt CO2-e)
Base case: Projected 2050
Scenario 1: emission reduction
466 TWh
120
Carbon reduction at 2012
Gas
62
Gas
Coal-CCS
Coal-CCS
Nuclear
Renewables
0
100
200
300
400
500
Clean Energy
100 TWh
Electricity (TWh)

Figure 4



Base case: Projected 2050
Scenario 2: emission reduction
466 TWh
120
Carbon reduction at 2012
Gas
62
Gas
Coal-CCS
Coal-CCS
Nuclear
Gas-CCS
Renewables
Carbon Emissions (Mt CO2-e)
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
Electricity (TWh)

Figure 5

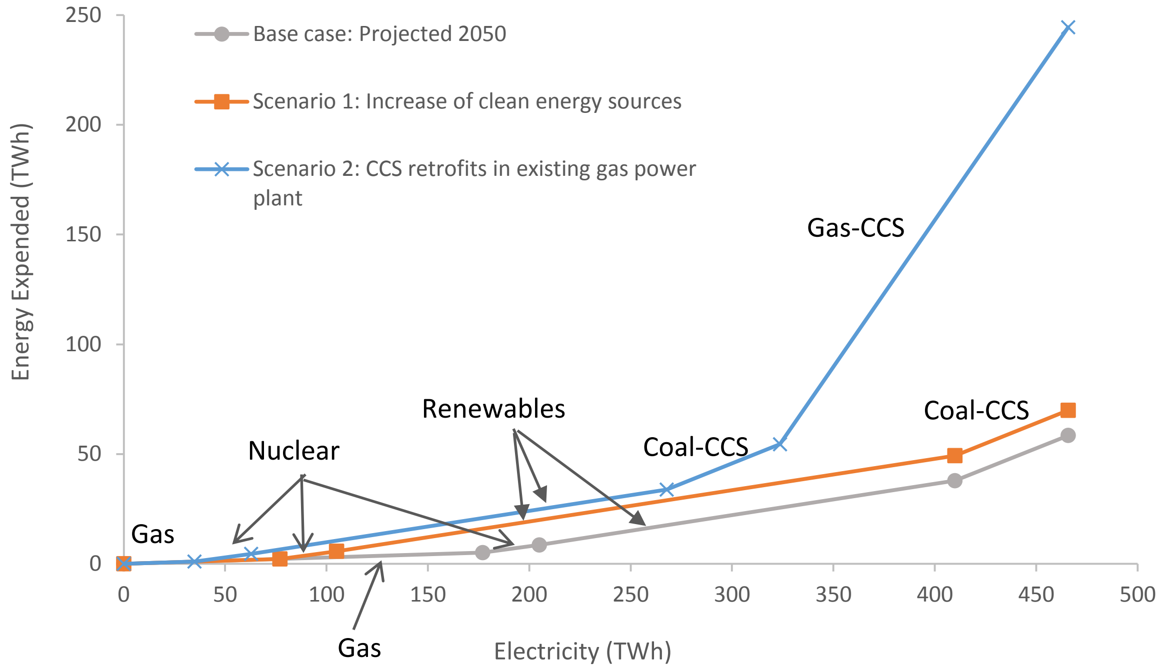
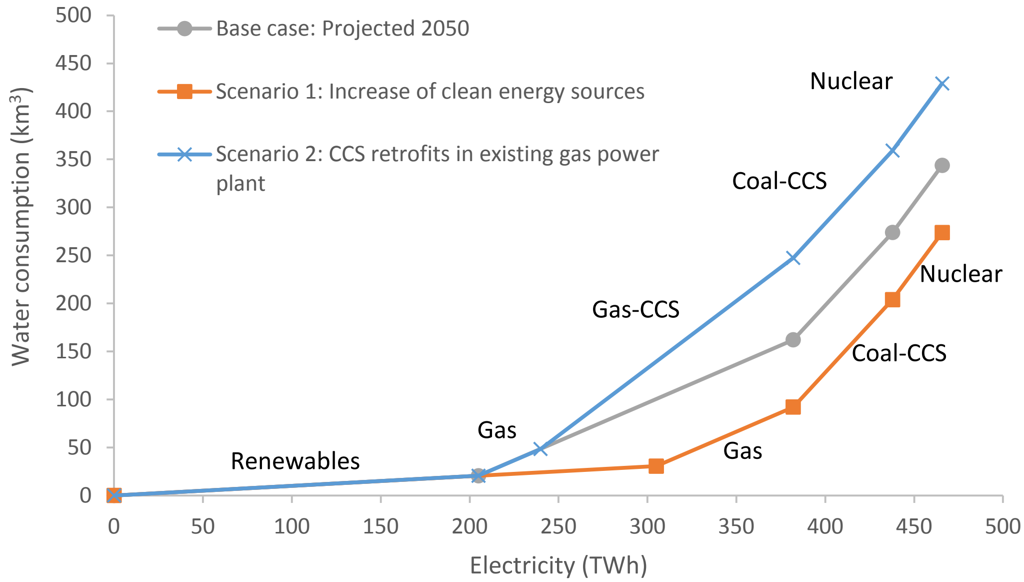
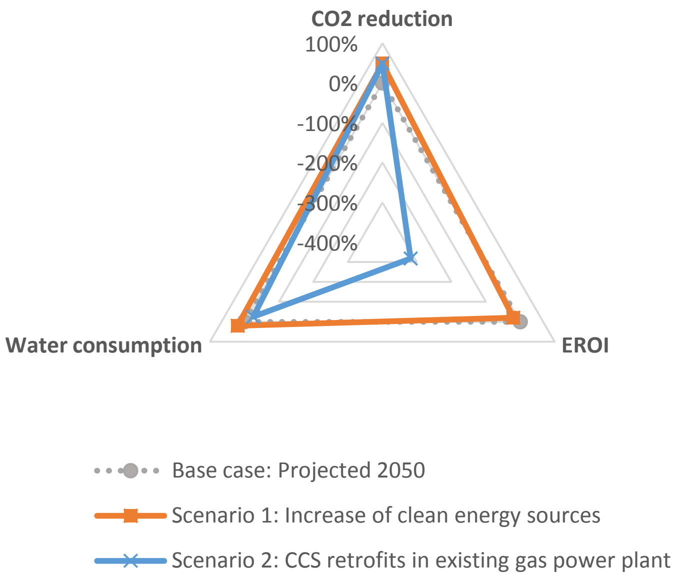

Base case: Projected 2050
Scenario 1: Increase of clean energy sources
Scenario 2: CCS retrofits in existing gas power plant
Energy Expended (TWh)
Electricity (TWh)
Gas
Nuclear
Renewables
Coal-CCS
Gas-CCS
Coal-CCS
Gas
0
50
100
150
200
250
0
50
100
150
200
250
300
350
400
450
500

Figure 6



Base case: Projected 2050
Scenario 1: Increase of clean energy sources
Scenario 2: CCS retrofits in existing gas power plant
Water consumption (km3)
Electricity (TWh)
500
450
400
350
300
250
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450
500
Renewables
Gas
Gas-CCS
Coal-CCS
Nuclear
Gas
Coal-CCS
Nuclear

figure 7


CO2 reduction
100%
0%
-100%
-200%
-300%
-400%
Water consumption
EROI
Base case: Projected 2050
Scenario 1: Increase of clean energy sources
Scenario 2: CCS retrofits in existing gas power plant